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ANALYSIS OF A BALANCED SHORT CIRCUIT ON A SULBAGSEL ELECTRICAL SYSTEM BY USING THE FFA-ABC METHOD APPROACH

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ABSTRACT
Fault studies are an important part of electrical power system analysis. The purpose of this study was to determine the amount of line current at the point of disturbance when a three-phase balanced fault occurs in the real Sulbagsel electrical system. In this paper, a new hybrid FFA-ABC (Fruit Fly Algorithm-Artificial Bee Colony) method is proposed, which is one of the new methods used to calculate balanced three-phase short circuit currents in electric power systems, especially in the real Sulbagsel electrical system of South Sulawesi, Indonesia. The real electricity system of Sulbagsel was chosen as the research object because this system consists of 15 generators, 44 buses, 52 transmission lines, and 29 load buses with system voltages varying from 30 kV, 70 kV, 150 kV, and 275 kV so that this system is included in the complex system category. To test the effectiveness of the proposed FFA-ABC method, it was implemented on a real electric power system, namely the Sulbagsel System. In addition, it can also be applied to IEEE electrical systems or other real electric power systems. The results of the new hybrid FFA-ABC method of the balanced short circuit analysis of the Sulbagsel electrical system are then compared using the FFA method, the ABC method, and the deterministic method (in this case, the bus impedance matrix (BIM) method). The simulation results obtained show that the FFA-ABC hybrid method is able to solve the problem of balanced short circuit analysis in the Sulbagsel electrical system in South Sulawesi, Indonesia which the largest fault current occurs when the fault is close to the slack bus generator (bus 2=Sidrap) of 18.9697 p.u, and the smallest fault current occurs when the fault is farthest from the slack bus generator (bus 44=Poso) of 0.8457 p.u.
Keywords: *ABC Method, Balanced Short Circuit, FFA Method, New FFA-ABC Hybrid Method, Bus Impedance Matrix, Sulbagsel Electrical System*

1. Introduction

Electricity is a major need for regions or countries whose economies are growing, the increasing need for electrical energy supplies for society and industry will continue to be sought to supply electrical power from power plants, both thermal generators and renewable energy generators, so that it remains available in both quantity and quality. Voltage stability and reliability of the electric power system are very important in the distribution of electrical energy from power plants to interconnected load centers to ensure uninterrupted electricity supply.

An electric power system under normal conditions is assumed to be a balanced three-phase system. The balanced state will be disturbed if there is a disturbance or short circuit in the components of the power system. In the event of a disturbance, the current flowing through the transmission network to the fault point is very large. The fault current is much greater than the maximum allowable current to flow in transmission lines, generators, or other equipment. If the safety devices do not work immediately, the very large current increase causes an increase in temperature, which can cause damage to the equipment or device. Short circuit disturbance is a type of disturbance that can cause the distribution of electrical energy to be hampered. Short circuit disturbances are usually caused by damage to the insulating material in the conductor and faults can damage electrical equipment if it is not equipped with a good protection system and correct. Therefore, special planning is needed to reduce the risk of these disturbances. One way to overcome this is to conduct a short circuit fault current analysis study. In the electric power system, there are three types of studies carried out to ensure the continuity of the generation and distribution of the electric power system: power flow studies, short circuit studies, and stability studies. Power flow studies are the determination or calculation of voltage, current, active power and reactive power found at various points of the electrical network in normal operating conditions, both currently running and those that are expected to occur in the future. The short circuit study is an analysis of the electricity network to determine the magnitude of the electrical fault, current, and voltage that occur on the bus that is experiencing interference and other buses in the interconnected electrical network system. While, Electric power system stability is the ability of the electric power system or its component parts to maintain synchronization and balance in the system. The system stability limit is the maximum power that flows through a point in the system without causing a loss of stability. In this research, researchers focused on short circuit studies to determine the magnitude of the fault current and voltage that occurs on the bus. The magnitude of the fault current in the system depends on the internal impedance of the generator plus the impedance of the system circuit. As in (Saadat, 1999), the balanced or symmetrical three-phase fault is defined as a disturbance that occurs in all phases and can be solved on a per-phase basis.

A short circuit is one of the disturbances in the electric power system that has transient characteristics that must be overcome by safety equipment. The occurrence of a short circuit causes a current surge with a magnitude higher than normal, and the voltage in that place becomes very low. Likewise, in (Sallam & Malik, 2019), the three-phase symmetrical short-circuit fault type is the most severe of the faults because it produces the highest short-circuit current of the same magnitude in each of the three phases. In (Murty, 2017), short circuit analysis is primarily required to compute the three-phase fault levels at one or more busses (nodes) in the electrical power system and evaluate the fault currents for faults on transmission lines and the corresponding contribution from the adjacent busses. Fault levels can be different for unloaded and loaded systems. When the fault level has to be computed considering loads, prefault bus voltages at the faulted nodes are required. These should be computed using a load flow program. Like in (Sabbir & Rashed, 2015), balanced three-phase faults can be analyzed using an equivalent single-phase circuit.

The aim of this research is to determine the magnitude of the largest and smallest fault currents that occur in the real electricity system of Sulbagsel. In this case, a study analysis of a balanced three-phase short circuit of the real Sulbagsel electrical power system was carried out using the new FFA-ABC hybrid method approach. The new FFA-ABC hybrid method combines two artificial intelligence methods, namely, the Fruit Fly Algorithm method (FFA method) and the Artificial Bee Colony method (ABC method). The selection of the hybrid FFA-ABC method in solving short circuit analysis problems in power systems is based on the characteristics of the FFA method and the ABC method in solving problems to get the best solution, namely (1) both of these methods are included in the computational method and quantitative method, (2) both of these methods are included in the heuristic method and the artificial intelligence category, (3) both of these methods are included in the swarm method, (4) both of these methods have quite fast computing times. The results of the new FFA-ABC hybrid method compare with the FFA method, the ABC method and deterministic method namely bus impedance matrix (BIM) method.

The fruit fly method (FFA) was introduced by Wen-Tsao Pan in 2012 (Wen-Tsao Pan, 2012). This method is a part of the artificial intelligence method and also heuristic method which works based on the sense of smell and sight of fruit flies which can collect aromas and food sources from the air even though the food source is 40 km away. While, the ABC method was introduced by D. Karaboga in 2007 (Karaboga & Basturk, 2008). This method works to solve complex problems (Nurlita Gamayanti, Abdullah Alkaff, 2015). In the ABC method, the bee colony consists of three groups of bees, namely employed bees, onlooker bees and scout bees. The first half of the colony consists of employed bees and the second half is the onlooker bees. For each food source, there is only one employed bee. In other words, the number of employed bees is equal to the number of food sources around the hive. The FFA and ABC methods have been widely used to solve complex problems in the financial sector, in the health sector, in the informatics sector, and in the electrical power sector.

The application of the FFA method in various sectors has been studied by several previous researchers, such as new fruit fly optimization algorithm: taking the financial distress model as an example (Wen-Tsao Pan, 2012) in the financial sector, a new fruit fly optimization algorithm enhanced support vector machine for diagnosis of breast cancer based on high-level features in the health sector (Huang et al., 2019) in the health sector, development of an optoelectronic sensor for detecting and classifying fruit fly (diptera: tephritidae) for use in real-time intelligent traps (Moraes, Nava, Scheunemann, & da Rosa, 2019) in the informatics sector, and several application of fruit fly method in the electrical power sector such as economic dispatch of power system based on improved fruit fly optimization algorithm (Liang, Zhang, Wang, & Jia, 2019), fruit fly optimization (FFO) for solving economic dispatch problem in power system (Geruna, Rul, et al., 2017), optimal sitting and parameter selection for fault current limiters considering optimal economic dispatch of generators (Guang, Xiaolong, & Mengzhou, 2018). Meanwhile, the application of the ABC method in various sectors has also been studied by several previous researchers, such as skin lesion segmentation method for dermoscopy images using artificial bee colony algorithm (Aljanabi, Özok, Rahebi, & Abdullah, 2018) in health sector, an efficient framework for remote sensing parallel processing: integrating the artificial bee colony algorithm and multiagent technology (Yang, Sun, & Li, 2019) in the informatic sector, Effects of memory and genetic operators on Artificial Bee Colony algorithm for Single Container Loading problem (Bayraktar, Ersöz, & Kubat, 2021) in transportation sector, and also several application of ABC method in the electrical power sector such as an improved local search involving bee colony optimization using lambda iteration combined with a golden section search method to solve an economic dispatch problem (Aurasopon & Khamsen, 2019), and optimal power sharing in microgrids using the artificial bee colony algorithm (Ullah, Jiang, Geng, Rahim, & Khan, 2022).

2. Literature Review

A literature review is an activity to review or review various literature previously published by academics or other researchers regarding the topic to be researched.

1. Balanced Short Circuit

One of the short circuit faults in the electric power system is a balanced short circuit fault or symmetrical short circuit fault. Therefore, several studies that have been conducted by previous researchers related to balanced short circuit analysis are described as follows: As (Sabbir & Rashed, 2015) describe, electrical power system fault analysis is the process of determining the bus voltage and line currents during the occurrence of various types of faults. The determination of the bus voltage and line currents is essential in the fault analysis of the electrical power system. The calculation process consists of various methods of mathematical calculation which are difficult to perform by hand, but can be easily done by using a computer device. Meanwhile, (Karthik, Shiva, Ali Siddique, & Shahabaz Ahmed, 2017) say that fault analysis is an important consideration in power system planning, protection equipment selection, and overall power system reliability assessment. Faults usually occur in a power system due to insulation failure, flashover, physical damage, or human error, and these faults may be three-phase in nature, involving all three phases in a balanced or symmetrical manner.

As in (Latt, 2019), an electrical fault in an electrical power system is the deviation of current and voltage from nominal values or states, and under steady-state operating conditions, electrical power system lines or types of equipment carry normal voltage and current, which results in a safer operation of the system network. If a fault occurs, it causes excessively high currents to flow, which cause damage to equipment and devices. Normally, fault analysis is calculated in per-unit quantities as it provides solutions that are somewhat consistent over different voltage and power ratings and operate on values of the order of unity. However, (O, A, & U, 2018) state that faults often occur in three-phase electrical power systems, and with the increasing demand for electrical power, one key challenge is the ability to identify and analyze these faults when they occur. A fault current is any abnormal electric current flowing through a nonrequired current, and in three-phase systems, a fault may involve one or more phases and ground or may occur only between phases. The prospective short circuit current of a predictable fault can be calculated for most situations. Likewise, in (Ghadban & AbdulWahhab, 2015), the short circuit problem is one of the most important and complex tasks in an electrical power system. Studies of these faults are necessary to ensure that the electrical power system is reliable, and the severity of the fault depends on the short circuit location, the path taken by the fault current, the system impedance, and its voltage level. Fault analysis is the process of evaluating the system voltages and currents under various types of short circuits.

The researcher (Brockhoeft, 2014) states that a balanced three-phase short circuit fault is defined as a simultaneous short circuit across all three phases of a transmission line, and a balanced three-phase fault is also called a symmetric fault because the power system remains in balance after the fault occurs, but if not cleared promptly, it can easily develop into a three-phase fault. Furthermore, in (Kakilli, 2013), a balanced three-phase fault current at a given bus of the system is calculated by using different methods, especially with the emphasis on the MVA method, compared to other conventional methods, and fault calculations provide information on the currents and voltage levels of an electrical power system during fault conditions. Sufficient accuracy in fault studies can be obtained with certain simplifications in the model of the power system. In (ETEBMS, 2017), short circuit analysis is performed to protect the system from any damage and limit the flow of current in the system. Short circuit analysis is done to determine the proper choice of protective devices, select efficient interrupting equipment, and verify the adequacy of the existing interrupting equipment. The analysis before the fault is carried out by solving the nonlinear load flow problem using the numerical iterative technique of the Newton-Raphson method. As in (Santamaria, 2011), the analysis of electrical power systems under fault conditions represents one of the most important and complex tasks in electrical power systems. The study of faults is necessary to ensure that the reliability and stability of the power system do not suffer a decrement as a result of a critical event such as a fault. Meanwhile, in (Gajbhiye, Kulkarni, & Soman, 2005), a fundamental principle that has been used in fault modeling is that the fault model should depict the change perceived by the network. Even in the three-phase domain, Thevenin's equivalent circuit representation is available for standard shunt faults, and a fault that involves multiple instances of either the same or different fault types will be referred to as a simultaneous fault.

A fault in a power system represents a structural network change equivalent to that caused by the addition of an impedance at the point of fault. If the fault impedance is zero, the fault is referred to as a bolted fault or a solid fault. In a balanced power system, there is no negative or zero sequence. The condition when a three-phase short circuit occurs can be seen in Figure 1.

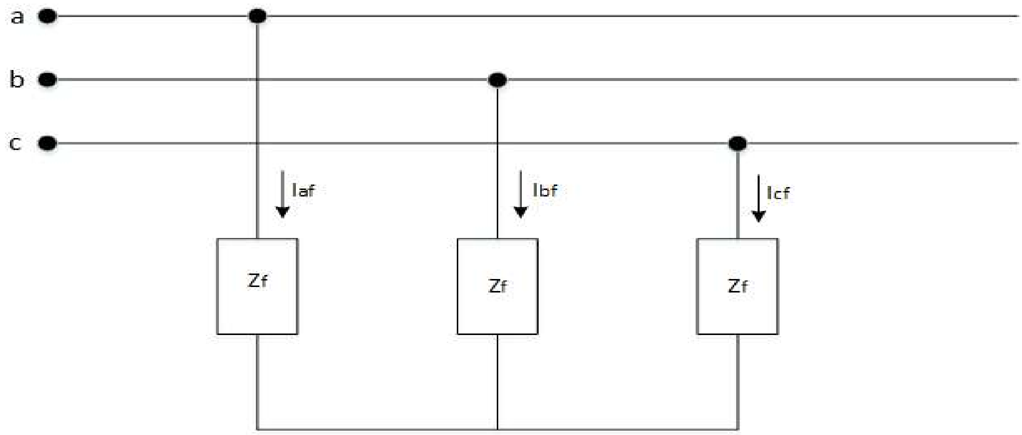

Fig. 1. Three-Phase Short-Circuit Fault

The faulted network is usually, but not always, assumed to be without load before the fault occurs. In the absence of loads, no prefault currents flow and there are no voltage differences across the branch impedances, and all bus voltages throughout the network are then the same as V_f, the prefault voltage at the fault point. Thus, the voltages at all buses of the network can be calculated using the prefault voltage Vf of the faulted bus and the elements in the column Z_{bus} corresponding to the faulted bus. According to (J.Grainger & William D.Stevenson, 2003), the calculated values of the bus voltage will yield the subtransient currents in the branches of the network if the system Z_{bus} has been formed with subtransient values for the machine reactances. If the three-phase fault occurs on bus k of a large-scale network, we can write it as:

$$I_f^{''} = \frac{V_f}{Z_{kk}}$$

Meanwhile, the voltage at any bus j during the fault is:

$$V_j = V_f - Z_{jk}.I_f^{"} = V_f - \frac{Z_{jk}}{Z_{kk}}V_f$$

where Z_{jk} and Z_{kk} are elements in column k of the system Z_{bus}. Furthermore, we can calculate the subtransient current $I_f^{"}$ from bus j to bus k in the line of impedance Zb connecting those two buses as:

$$I_{ij}^{"} = \frac{V_i - V_j}{Z_b} = -I_f^{"}\left(\frac{Z_{ik} - Z_{jk}}{Z_b}\right) = -\frac{V_f}{Z_b}\left(\frac{Z_{ik} - Z_{jk}}{Z_{kk}}\right)$$

2. Fruit Fly Algorithm (FFA) Method

The FFA was introduced by Wen-Tsao Pan in 2012 (Wen-Tsao Pan, 2012) to solve complex problems that occur specifically in the financial sector. This FFA method works based on the sense of smell and sight which can detect the location of food sources that are quite far away. An illustration of fruit flies searching for and finding their food source is shown in Figure 2.

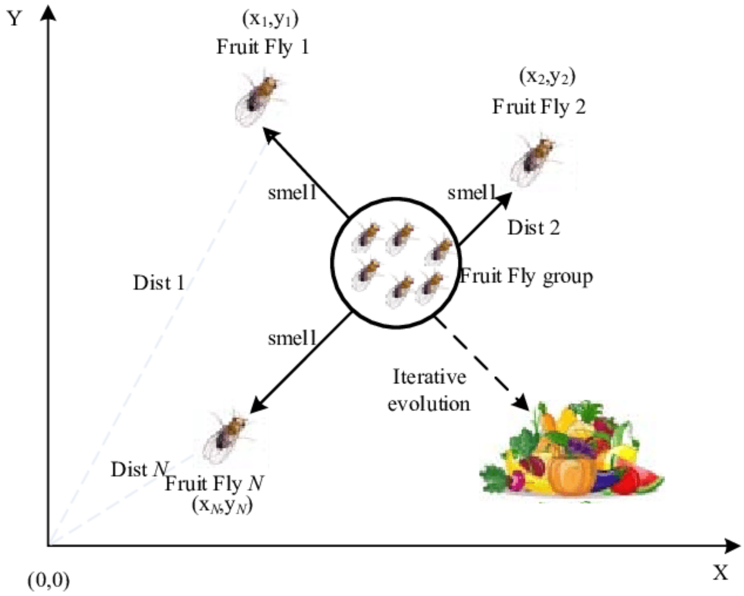

Fig. 2. Foraging scheme in fruit fly swarms (Geruna, Abdullah, et al., 2017)

The FFA method has advantages in terms of simple computational processes and ease in transforming concepts into program code. This FFA method is represented in the following steps:

a. Determine the starting position of the fruit fly swarm
   X_{axis} and Y_{axis}
b. Find the direction and distance of food sources randomly using the fruit fly's sense of smell
   X_i=X_{axis}+random value
   Y_i=Y_{axis}+random value
c. Predict the distance of origin of fruit flies (Dist) because the location of the food is unknown by calculating the smell concentration value (S)

$$\text{Dist}_i = \sqrt{X_i^2 + Y_i^2}$$

$$S_i = \frac{1}{\text{Dist.}_i}$$

d. Substitute the smell concentration value (S) into the smell concentration variable (Smell)
   $Smell_i$=function(S_i)
e. Determine the maximum smell concentration among a swarm of fruit flies
   [bestSmell, bestIndex]=max(Smell)
f. Maintain the best values of X, Y coordinates and smell concentration

X_{axis}=X(bestIndex)
Y_{axis}=Y(bestIndex)
Smellbest=bestSmell

g. Go to loop optimization, and repeat steps 2 to 5 and see when the current Smell concentration is better than the previous Smell concentration, if that is true, then execute step f.

3. Artificial Bee Colony (ABC) Method

The ABC method was developed by D. Karaboga in 2007 (Karaboga & Basturk, 2008). In the ABC method, the bee colony consists of three groups of bees, namely employed bees, onlooker bees and scout bees. Onlooker bees choose a food source depending on the probability value associated with the food source P_i calculated using Equation 14.

$$P_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n}$$

where fit_i is the fitness value of solution i which is proportional to the amount of nectar from the food source at position i and SN is the number of food sources which is equal to the number of employed bees. The candidate food positions of the old ones in memory will be generated according to the equation 15.

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj})$$

where k∈{1,2,…..,SN} and j∈{1,2,….,D} are randomly selected indices. ϕ_{ij} is a random number between [-1,1].

This ABC method is represented in the following steps:

a. Enter the bee swarm parameters
b. Initialize the position of the bee colony
c. Calculate the fitness function
d. Find the minimum fitness
e. Enter the employed bee phase by finding new solutions
f. Evaluation of new solutions from the employed bee phase
g. Calculate the probability according to equation 14

$$P_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n}$$

h. Enter the onlooker bee phase to find new solutions
i. Evaluation of new solutions from the onlooker bee phase
j. Find the new fitness minimum of the onlooker bee phase
k. Enter the scout bee phase
l. Calculate fitness solution

3. Research Methods

Research or research comes from English (research), which means the process of gathering information with the aim of improving, modifying, or developing an investigation or research group. The type of research conducted by researchers is non-experimental quantitative research that is ex post facto, in which all data is processed based on existing data. Non-experimental research is research in which observations are made of research subjects according to their circumstances, without any manipulation (intervention) from researchers, and also aims to describe the situation and conditions of the research object.

The data collection technique used in this study was a literature study and secondary data collection.

1. Literature study

According to experts, the definition and understanding of literature study explain that literature study is the study of various reference books and similar previous research results in various publications that are useful for obtaining a theoretical basis on the problem to be studied and is a data collection technique by conducting a review of various books, literature, and various reports relating to the problem to be solved.

2. Secondary data collection

The secondary data collection method is often called the method of using document materials, because in this case the researcher does not directly collect the data himself but examines and utilizes data or documents produced by other parties.

Data is a description of objects, events, activities, and transactions that have no meaning or have no direct effect on the user. The data used by the researchers in this case is secondary. Secondary data is data obtained by researchers from existing sources in the form of:

a. Single line diagram
b. Line data
c. Generator data
d. Load Data
e. Dynamic parameter data of generator

The test data was taken from the data interconnection electricity system of Sulawesi of South Part (Sulbagsel), South Sulawesi in Indonesia (Ansar Suyuti, Indar Chaerah Gunadin, 2017). Single line diagram of this interconnection electricity system shown in Figure 3.

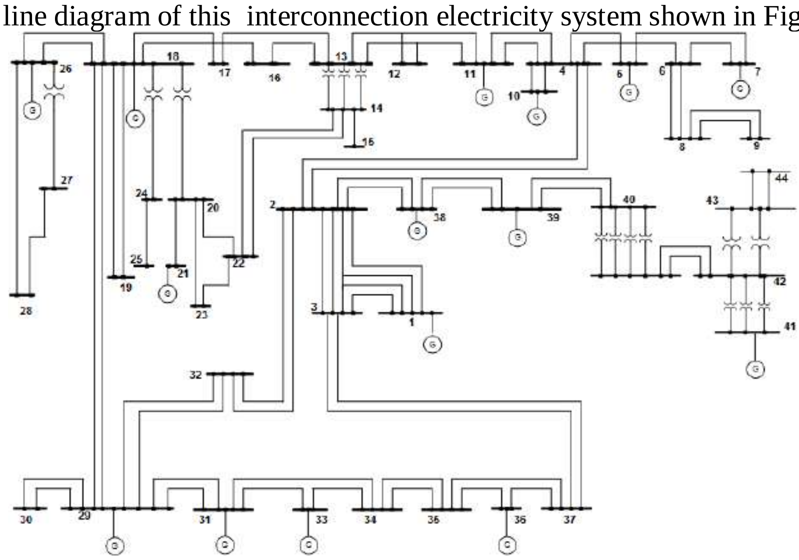

Fig. 3. Single line diagram of the interconnection electricity system of the Sulbagsel.

Where:

bus 1= Sengkang 150
bus 2= Sidrap 150
bus 3= Soppeng 150
bus 4= Pare-Pare 150
bus 5= Pinrang 150
bus 6= Polmas 150
bus 7= Bakaru 150
bus 8= Majene 150
bus 9= Mamuju 150
bus 10= Suppa 150
bus 11= PLTU Barru 150
bus 12= Barru 150
bus 13= Pangkep 150
bus 14= Pangkep 70
bus 15= Tonasa 70
bus 16= Bosowa 150
bus 17= Kima 150
bus 23= Daya 70
bus 24= Tallo 30
bus 25= Barawaja 150
bus 26= Tallo Lama 150
bus 27= Tallo Lama 70
bus 28= Bontoala 150
bus 29= Sungguminasa 150
bus 30=Tanjung Bunga 150
bus 31= Tallasa 150
bus 32= Maros 150
bus 33= Punagaya 150
bus 34= Jeneponto 150
bus 35= Bulukumba 150
bus 36= Sinjai 150
bus 37= Bone 150
bus 38= Makale 150
bus 39= Palopo 150

bus 18= Tallo 150
bus 19= Panakukang 150
bus 20= Tallo 70
bus 21= Borongloe 150
bus 22= Mandai 70
bus 40= Ltupa 150
bus 41= PLTA Poso
bus 42= Pamona 275
bus 43= Pamona 150
bus 44= Poso

The real Sulbagsel interconnection electricity system operates at transmission line voltages of 30 kV, 70 kV, 150 kV, and 275 kV. The data for the real Sulbagsel Electrical System Transmission Line can be seen in Table 1. The data on the generator and load of the Sulbagsel Electrical System can be seen in Table 2. While the data for the generator dynamic parameters of the Sulbagsel electrical system can be seen in Table 3.

Table 1 - Transmission Line Data Of Sulbagsel Electrical System

From line	to line	R (PU)	X (PU)	1/2 B (PU)
1	2	0.01058	0.07259	0.00342
1	3	0.02106	0.1267	0.00404
2	3	0.05643	0.20275	0.00482
2	4	0.02003	0.07198	0.00142
4	5	0.01388	0.04974	0.00067
4	10	0.00787	0.02826	0.00056
4	11	0.01	0.07946	0.00396
4	6	0.03663	0.13159	0.01819
5	7	0.03076	0.11023	0.01012
6	7	0.02627	0.0944	0.00743
6	8	0.05261	0.18902	0.00372
8	9	0.03076	0.11023	0.01012
11	12	0.01173	0.03973	0.00198
12	13	0.02419	0.08667	0.01167
13	14	0	0.39492	0
13	16	0.0109	0.03919	0.00493
13	17	0.00845	0.03024	0.0038
14	15	0.03275	0.06013	0.00005
14	22	0.36318	0.66671	0.0005
16	18	0.04764	0.17071	0.00575
17	18	0.00845	0.03024	0.0038
18	26	0.00726	0.026	0.00088
18	19	0.04334	0.07958	0.00006
18	29	0.00385	0.02635	0.00124
18	20	0	0.41587	0
18	24	0	0.5535	0
26	27	0	0.41587	0
27	28	0.04046	0.07428	0.00006
20	21	0.06069	0.11141	0.00034
20	22	0.05828	0.10699	0.00032
20	23	0.02408	0.04421	0.00013
22	23	0.0342	0.06278	0.00019
24	25	0.12292	0.17508	0.00002
29	30	0.00707	0.04256	0.00136
29	31	0.0097	0.06649	0.00314
29	32	0.05433	0.37234	0.01756
31	33	0.01756	0.04609	0.00217
31	34	0.03241	0.13837	0.01973
33	34	0.0097	0.06649	0.00314
34	35	0.04861	0.17466	0.00344
35	36	0.0312	0.11211	0.00882
36	37	0.01149	0.14603	0.01149
35	37	0.0312	0.11211	0.00882
37	3	0.04578	0.16306	0.00402
2	32	0.01235	0.08464	0.00399
2	38	0.06274	0.37753	0.01203
38	39	0.03917	0.14076	0.00277
39	40	0	0.17234	0
40	42	0.051	0.38	0.00134
41	42	0	0.013	0
42	43	0.01914	0.06356	0.00018
43	44	0.01604	0.13353	0.00667

Table 2 - The Data of Generator and Load of Sulbagsel Electrical System

Bus	Voltage Mag	Load		Generator			
		MW	Mvar	MW	Mvar	Q max	Q min
1	1.02	28.4	11.5	265.2	7.9	300	80
2	1.01	26.5	10.3	0.0	0.0	0	0
3	1.02	14.1	3.4	0.0	0.0	0	0
4	1.00	18.7	4.7	0.0	0.0	0	0
5	1.00	24.4	6.2	14.3	0.8	200	50
6	1.01	17.1	4.1	0.0	0.0	0	0
7	1.03	3.5	0.2	63.0	3.1	500	100
8	1.00	23.3	3.7	0.0	0.0	0	0
9	1.00	9.6	4.8	0.0	0.0	0	0
10	1.00	0.0	0.0	31.1	8.2	300	80
11	1.00	0.0	0.0	60.4	4.8	150	50
12	1.00	10.1	2.4	0.0	0.0	0	0
13	0.97	22.1	8.0	0.0	0.0	0	0
14	1.00	0.0	0.0	0.0	0.0	0	0
15	1.00	18.9	10.6	0.0	0.0	0	0
16	1.00	33.1	15.4	0.0	0.0	0	0
17	1.00	18.0	5.8	0.0	0.0	0	0
18	0.97	63.3	18.3	21.0	7.9	200	50
19	0.97	68.3	17.7	0.0	0.0	0	0
20	0.96	0.0	-20.0	0.0	0.0	0	0
21	0.94	11.4	0.0	5.2	0.2	200	50
22	1.00	24.3	2.6	0.0	0.0	0	0
23	0.98	24.5	2.8	0.0	0.0	0	0
24	1.00	0.0	0.0	0.0	0.0	0	0
25	1.00	0.0	0.0	0.0	0.0	0	0
26	0.97	19.7	4.7	12.6	0.0	150	50
27	0.97	0.0	0.0	0.0	0.0	0	0
28	1.00	26.5	7.7	0.0	0.0	0	0
29	0.98	15.7	3.6	20.0	5.9	150	50
30	1.00	55.2	16.7	0.0	0.0	0	0
31	0.99	20.6	4.7	79.0	39.1	150	50
32	1.00	18.6	5.5	0.0	0.0	0	0
33	1.00	0.0	0.0	196.1	38.6	300	80
34	1.00	17.4	3.4	0.0	0.0	0	0
35	1.00	27.1	6.5	0.0	0.0	0	0
36	1.00	21.9	4.6	4.0	0.5	200	50
37	1.00	32.1	8.2	0.0	0.0	0	0
38	1.02	11.9	1.5	8.2	2.1	200	50
39	1.00	49.2	0.0	4.0	2.0	120	50
40	1.00	0.0	0.0	0.0	0.0	0	0
41	1.00	0.0	0.0	195.0	27.2	300	50
42	1.00	0.0	0.0	0.0	0.0	0	0
43	1.00	4.9	0.5	0.0	0.0	0	0
44	1.00	11.0	1.8	0.0	0.0	0	0

Table 3 - The Data of Generator Dynamic Parameters of Sulbagsel Electrical System

Number	Generator	R_a	X'_d
1	Sengkang	0	0.2000
2	Pinrang	0	0.3850
3	Bakaru	0	0.2680
4	Suppa	0	0.3850
5	PLTU Barru	0	0.1990
6	Tello	0	0.0995
7	Barangloe	0	0.3850
8	Tallo Lama	0	0.1990
9	Sungguminasa	0	0.3850
10	Tallasa	0	0.3850
11	Punagaya	0	0.3850
12	Sinjai	0	0.2680
13	Makale	0	0.3850
14	Palopo	0	0.3850
15	PLTA Poso	0	0.2680

One method that is used to solve problems related to balanced short circuit analysis is the artificial intelligence method. In this paper, the method used is the new FFA-ABC hybrid method. The selection of the new hybrid FFA-ABC method in solving short circuit analysis problems in power systems is based on the characteristics of the FFA method and the ABC method in solving problems to get the best solution, namely (1) both of these methods are included in the computational method and quantitative method, (2) both of these methods are included in the heuristic method and the artificial intelligence category, (3) both of these methods are included in the swarm method, (4) both of these methods have quite fast computing times. This FFA-ABC method has a smaller error than the FFA and ABC methods and the value obtained is close to the value obtained by the deterministic bus impedance matrix method. The parameters of the FFA and ABC methods are determine by the population size which is the same as the number of buses in the Sulbagsel system, namely n=44, the maximum number of iterations is maxit=100, the dimensions of the test function are the same as the number of generator data, namely dim=15, the upper limit (ub) and the upper limit (lb) of the test function, the number of food sources equal to half the colony size, namely food number=n, and the food source limit. The probability is calculated based on equation 14 by finding the fitness function value of the employed bee phase. The fitness function is obtained by entering line data parameters, generator data to obtain the Y_{bus} matrix. Then run the load flow by entering the bus data parameters. Calculates symmetry fault by entering line data parameters. The software used to implement and run the FFA-ABC method is Matlab version R2017a.

In the new FFA-ABC hybrid method, the FFA method, and the ABC method, the distance traveled by a swarm of fruit flies (FFA) and a swarm of bee colonies (ABC) to get the best solution is carried out at the test limits (-2, 2). As in (Haripuddin, Suyuti, Mawar Said, & Syam Akil, 2020), the main program of the new FFA-ABC hybrid method is the FFA method, where the fitness function and the index of the FFA swarm become inputs for the ABC swarm.

The algorithm procedure of the new FFA-ABC hybrid method approach proposed is described as follows (Haripuddin et al., 2020):

1. Enter the parameters FFA and ABC
2. Determine the position of the X_{axis} and Y_{axis} of FFA
3. Calculate the distance and the solution of FFA using the equation:

$$\mathrm{Dist}_i = \sqrt{X_i^2 + Y_i^2}$$

$$S_i = \frac{1}{\mathrm{Dist}_i}$$

4. Calculate the fitness function using the equation:
   fitness(i) = ObjectFunct(Si)
5. Find the fitness minimum and index of FFA

[bestSmell,index] = max(Fitness)
6. Determine the value of solution ABC (ObjVal) based on step 5
7. Calculate the objective variable using the Equation:
   fitness = Object Funct(ObjVal)
8. Reset ABC trial counter
9. Remember ABC's Best Food (GlobalMin, and GlobalParams)
10. Enter into the main iterative, start iteratively from the employed bee phase.
11. Calculate the probability using equation:
   prob = (0.9 * fitness/max(fitness)) + 0.1
12. Enter the onlooker bee iterative phase
13. Remember ABC's Best Food Sources (GlobalMin, and GlobalParams)
14. Enter the Scout bee phase
15. Set the food source whose trial counter exceeds the limit value
16. Enter the iterative phase of FFA
17. Update the new X_{axis} and Y_{axis} positions of FFA
18. Calculate the distance and the new FFA solution using the equation:

$$\mathrm{Dist}_i = \sqrt{X_i^2 + Y_i^2}$$

$$S_i = \frac{1}{\mathrm{Dist}_i}$$

19. Repeat steps 4 and 5
20. If the new value is less than the best value. Next, update the best value
21. Find the Smellbest of FFA and best of FFA
22. If the updated FFA best value (Smellbest) is less than or equal to ABC's best food source or vice versa, and the best FFA index is less than or equal to ABC's GlobalParams index or vice versa, then Smellbest of FFA value equals global of ABC or vice versa, and the best index of FFA equals GlobalParams index of ABC or vice versa

4. Results and Discussions

Balanced short circuit testing is carried out on load buses that have a large enough load in the Sulbagsel interconnection electrical system. Tests were also carried out on the load bus, which was close to the slack bus (the Sengkang bus), and on the load bus, which was far from the Sengkang bus. Buses with a fairly large load are bus 19 (Panakukang bus) with a load of 68.3 MW, bus 30 (Tanjungbunga bus) with a load of 55.2 MW, and bus 39 (Palopo bus) with a load of 49.2 MW. While the closest bus to the Sengkang bus is bus 2 (Sidrap bus) with a load of 26.5 MW, the furthest bus from the Sengkang bus is bus 44 (Poso bus) with a load of 11 MW. Testing of the three-phase balanced short circuit of the Sulbagsel electrical system was carried out using the FFA-ABC hybrid method. The test results of the FFA-ABC hybrid method are compared with the results of the FFA method, the ABC method, and the bus impedance matrix method.

The magnitude of the bus voltage and line current from the balanced three-phase short circuit test using the FFA-ABC hybrid method on bus 19 (Panakukang bus), a bus that has a large load in the Sulbagsel interconnection electrical system of 68.3 MW, is shown in Tables 4 and 5. The characteristic curve of the bus voltage magnitude during faults on the Panakukang bus per unit using the FFA-ABC hybrid method is shown in Figure 4.

Table 4 - Bus Voltage Magnitude During Fault at Panakukang Bus Per Unit Using The New Ffa-Abc Hybrid Method

Bus Number	Voltage Magnitude	Angle degrees
1	0.9421	-0.2149
2	0.9238	-2.4897
3	0.9185	-3.7368
4	0.9689	-5.6034
5	0.9984	-5.4861
6	1.0230	-6.3643
7	1.0447	-4.7587
8	1.0105	-9.3183
9	1.0063	-9.8022
10	0.9820	-5.2691
11	0.9059	-9.4009

Bus Number	Voltage Magnitude	Angle degrees
12	0.8403	-12.1348
13	0.6547	-17.8920
14	0.8263	-22.8894
15	0.8415	-23.9892
16	0.6243	-18.3124
17	0.5794	-18.4882
18	0.5043	-19.0508
19	0.0000	0.0000
20	0.6328	-19.9355
21	0.6346	-20.0221
22	0.6454	-20.9393
23	0.6375	-20.5674
24	0.5094	-19.0509
25	0.5094	-19.0509
26	0.5127	-19.1371
27	0.5125	-19.8349
28	0.5123	-20.1538
29	0.5562	-14.6026
30	0.5549	-14.8389
31	0.6137	-5.6307
32	0.8498	-5.2398
33	0.6448	-2.3721
34	0.6649	-4.0599
35	0.7817	-6.9243
36	0.8178	-7.7061
37	0.8265	-6.8997
38	0.9374	20.5336
39	0.9236	30.5308
40	0.7453	50.1911
41	0.9275	104.0753
42	0.9135	102.6005
43	0.9197	102.0623
44	0.9173	101.2716

Table 5 - Line Currents For Fault At Panakukang Bus Per Unit Using The Ffa-Abc Hybrid Method

From Bus	To Bus	Current Magnitude	Angle degrees
1	2	0.5663	-19.2687
1	3	0.4852	-14.8309
2	3	0.1029	-2.2790
2	4	0.9161	52.6851
2	32	0.9997	-55.4698
3	37	0.6155	-51.7423
4	11	1.1077	-45.6091
4	6	0.4074	83.3431
5	4	0.5729	-75.9861
6	8	0.2784	-5.6506
7	5	0.4256	-62.6560
7	6	0.3768	-26.4462
8	9	0.0931	-19.0712
10	4	0.4884	-56.3979
11	12	1.8754	-51.8324
12	13	2.2284	-67.1633
13	14	0.4638	48.9669
13	16	0.7575	-83.5620
13	17	2.4080	-87.6491
14	15	0.3224	48.6432
16	18	0.6797	-89.3355
17	18	2.3997	-89.0579
18	26	0.3138	81.2411
18	19	5.5649	-80.4774
18	20	0.3097	66.5985
18	24	0.0092	70.9381
19	F	5.8122	-77.7252
20	21	0.0165	70.5920
20	22	0.1384	56.4239

From Bus	To Bus	Current Magnitude	Angle degrees
20	23	0.1686	42.6447
22	14	0.2404	88.7097
23	22	0.1238	69.7016
24	25	0.0000	-17.0678
26	27	0.0150	-21.7461
27	28	0.0338	5.8158
29	18	2.4888	-60.1060
29	30	0.0618	-34.6299
31	29	1.6087	-33.8477
32	29	0.8417	-69.2849
33	31	0.9619	-24.0642
33	34	0.4162	51.0929
34	31	0.3878	-61.1089
34	35	0.6742	82.6559
35	36	0.3245	80.2088
37	36	0.1069	-36.9292
37	35	0.3871	-79.8824
38	2	0.9824	16.4438
39	38	1.1163	45.9158
40	39	1.9421	72.0101
41	42	2.1169	72.7646
42	40	1.9517	72.4192
43	42	0.1602	-24.8618
44	43	0.0899	-82.7167

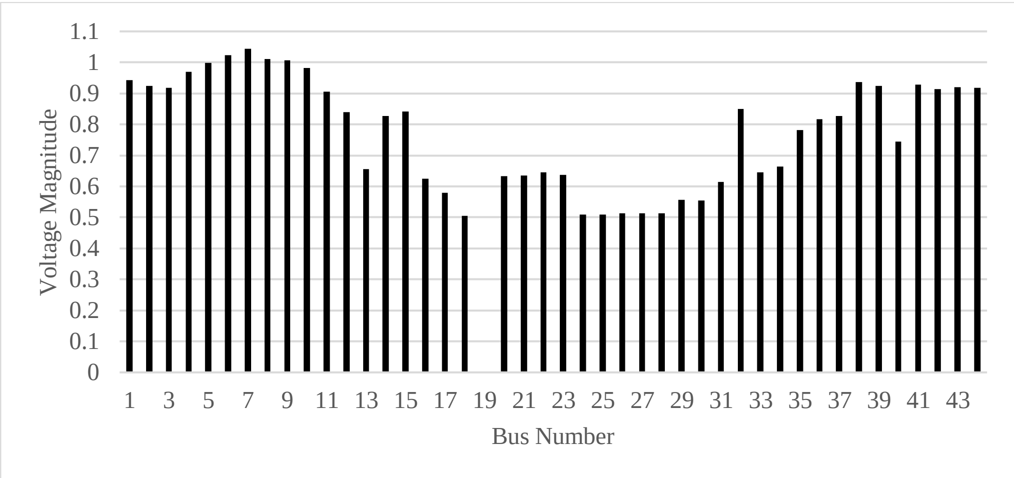

Fig. 4. Curves of The Bus Voltage Magnitude Per Unit Fault at Panakukang Bus Using The FFA-ABC Hybrid Method

Next, the comparison of the simulation results of a balanced three-phase short circuit using the FFA-ABC hybrid method with the FFA method, the ABC method, and the Bus Impedance Matrix method (BIM) for line currents per unit during a fault at the Panakukang bus is shown in Table 6.

Table 6 - The Comparison of The Simulation Results of a Balanced Three-Phase Short Circuit For Fault at The Panakukang Bus

From	To	Line Current Magnitude			
		Method			
		FFA-ABC	FFA	ABC	BIM
1	2	0.5663	0.5654	0.5648	0.5674
1	3	0.4852	0.4847	0.4843	0.4858
2	3	0.1029	0.1029	0.1029	0.1030
2	4	0.9161	0.9157	0.9153	0.9167
2	32	0.9997	0.9994	0.9992	1.0000
3	37	0.6155	0.6153	0.6151	0.6157
4	11	1.1077	1.1074	1.1072	1.1081
4	6	0.4074	0.4074	0.4074	0.4073
5	4	0.5729	0.5728	0.5728	0.5731
6	8	0.2784	0.2781	0.2779	0.2787
7	5	0.4256	0.4255	0.4255	0.4256

From	To	Line Current Magnitude			
		Method			
		FFA-ABC	FFA	ABC	BIM
7	6	0.3768	0.3765	0.3763	0.3772
8	9	0.0931	0.0930	0.0929	0.0932
10	4	0.4884	0.4881	0.4880	0.4887
11	12	1.8754	1.8747	1.8743	1.8763
12	13	2.2284	2.2280	2.2278	2.2287
13	14	0.4638	0.4637	0.4637	0.4638
13	16	0.7575	0.7575	0.7574	0.7576
13	17	2.4080	2.4082	2.4084	2.4077
14	15	0.3224	0.3224	0.3225	0.3223
16	18	0.6797	0.6798	0.6799	0.6796
17	18	2.3997	2.4000	2.4001	2.3994
18	26	0.3138	0.3138	0.3137	0.3138
18	19	5.5649	5.5649	5.5649	5.5649
18	20	0.3097	0.3097	0.3097	0.3097
18	24	0.0092	0.0092	0.0092	0.0092
19	F	5.8122	5.8124	5.8125	5.8119
20	21	0.0165	0.0165	0.0164	0.0165
20	22	0.1384	0.1384	0.1384	0.1383
20	23	0.1686	0.1685	0.1685	0.1686
22	14	0.2404	0.2405	0.2405	0.2404
23	22	0.1238	0.1238	0.1239	0.1237
24	25	0.0000	0.0000	0.0000	0.0000
26	27	0.0150	0.0149	0.0148	0.0152
27	28	0.0338	0.0337	0.0336	0.0339
29	18	2.4888	2.4883	2.4879	2.4895
29	30	0.0618	0.0615	0.0613	0.0621
31	29	1.6087	1.6078	1.6073	1.6097
32	29	0.8417	0.8417	0.8416	0.8418
33	31	0.9619	0.9614	0.9610	0.9625
33	34	0.4162	0.4160	0.4159	0.4165
34	31	0.3878	0.3878	0.3877	0.3878
34	35	0.6742	0.6742	0.6742	0.6742
35	36	0.3245	0.3244	0.3244	0.3246
37	36	0.1069	0.1068	0.1068	0.1069
37	35	0.3871	0.3871	0.3872	0.3871
38	2	0.9824	0.9821	0.9819	0.9828
39	38	1.1163	1.1159	1.1156	1.1168
40	39	1.9421	1.9390	1.9371	1.9457
41	42	2.1169	2.1136	2.1115	2.1206
42	40	1.9517	1.9485	1.9466	1.9553
43	42	0.1602	0.1602	0.1601	0.1603
44	43	0.0899	0.0898	0.0897	0.0900

The voltage intervals considered by Enrique Acha, Claudio R. Fuerte-Esquivel, Hugo Ambriz-Perez, and Cesar Angeles-Camacho in the modeling and simulation of the power grid are –5% and +5% of the nominal voltage. Therefore, the minimum and maximum allowable voltage in the power system are 0.95 pu - 1.05 pu. The results of the analysis of the three-phase balanced short circuit of the Sulbagsel electrical system when the fault occurs on the Panakukang bus (bus 19) as shown in Table IV show that the system conditions are mostly experiencing voltage instability and voltage drops. Voltage stability conditions occur only on bus 4 (Pare-Pare bus), bus 5 (Pinrang bus), bus 6 (Polmas bus), bus 7 (Bakaru bus), bus 8 (Majene bus), bus 9 (Mamuju bus), and bus 10 (Suppa bus) are at 0.95 - 1.05 pu voltage. The magnitude of the largest voltage drop that can cause a voltage collapse is on bus 18 (Tello bus) of 0.5043 pu. The total amount of fault current on bus 19 (Panakukang bus), namely, the bus experiencing disturbances, is 5.8122 pu such as shown in Table 5. Comparison of the total fault current on the Panakkang bus using the hybrid FFA-ABC method, FFA method, ABC method, and bus impedance matrix method is shown in Table 6, namely 5.8122 p.u, 5.8124 p.u, 5.8125, and 5.8119 p.u. This shows that the results obtained with the hybrid FFA-ABC method are close to the results obtained by the bus impedance matrix method with smaller errors when compared with the FFA method and the ABC method.

Meanwhile, the magnitude of the bus voltage and line current from the balanced three-phase short circuit test using the FFA-ABC hybrid method on bus 30 (Tanjungbunga bus), a bus that has a large load in the Sulbagsel interconnection electrical system of 55.2 MW is shown in Table 7 and 8. The curf of the bus voltage magnitude during faults on the Tanjungbunga bus per unit using the FFA-ABC hybrid method are shown in Figure 5.

Table 7 - Bus Voltage Magnitude During Fault at Tanjungbunga Bus Per Unit Using The New Ffa-Abc Hybrid Method

From Bus	To Bus	Current Magnitude	Angle deegres
1	2	0.5434	-29.1307
1	3	0.4888	-27.6015
2	3	0.1119	-20.3613
2	4	1.1232	61.5548
2	32	1.3369	-69.5343
3	37	0.8456	-72.1136
4	11	1.0688	-54.6168
4	6	0.5195	80.8997
5	4	0.6950	-82.9043
6	8	0.2819	0.8232
7	5	0.4615	-67.2745
7	6	0.3678	-22.9250
8	9	0.0921	-13.5908
10	4	0.5129	-62.4324
11	12	1.8329	-59.8021
12	13	2.2775	-77.7102
13	14	0.5839	45.4297
16	13	0.7917	84.7896
17	13	2.7352	80.8745
18	16	0.7948	79.0341
18	17	2.7726	79.6926
18	19	0.1463	87.4708
18	20	0.4441	67.7910
18	24	0.0079	82.9458
20	21	0.0327	77.5743
20	22	0.1929	50.9488
20	23	0.2475	45.0397
22	14	0.2654	72.8043
23	22	0.1563	57.5916
24	25	0.0000	-28.4119
26	18	0.3872	-86.5551
26	27	0.0666	70.6419
27	28	0.0829	56.4499
29	18	4.5985	85.8399
29	30	7.2668	-85.5727
30	F	7.5312	-83.2406
31	29	1.4619	-49.7103
32	29	1.2183	-83.6190
33	31	0.8240	-39.5541
33	34	0.6077	78.2790
34	31	0.5228	-71.0736
34	35	1.0679	87.3547
35	36	0.4240	82.8051
37	36	0.1769	-81.0135
37	35	0.6324	-87.7401
38	2	0.9643	16.2057
39	38	1.0908	46.1330
40	39	1.8822	73.4304
41	42	2.0569	74.4657
42	40	1.8978	73.9657
43	42	0.1577	-20.8837
44	43	0.0847	-78.5880

Table 8 - Line Currents For Fault at Tanjungbunga Bus Per Unit Using The New Ffa-Abc Hybrid Method

From Bus	To Bus	Current Magnitude	Angle deegres
1	2	0.5434	-29.1307
1	3	0.4888	-27.6015

From Bus	To Bus	Current Magnitude	Angle deegres
2	3	0.1119	-20.3613
2	4	1.1232	61.5548
2	32	1.3369	-69.5343
3	37	0.8456	-72.1136
4	11	1.0688	-54.6168
4	6	0.5195	80.8997
5	4	0.6950	-82.9043
6	8	0.2819	0.8232
7	5	0.4615	-67.2745
7	6	0.3678	-22.9250
8	9	0.0921	-13.5908
10	4	0.5129	-62.4324
11	12	1.8329	-59.8021
12	13	2.2775	-77.7102
13	14	0.5839	45.4297
16	13	0.7917	84.7896
17	13	2.7352	80.8745
18	16	0.7948	79.0341
18	17	2.7726	79.6926
18	19	0.1463	87.4708
18	20	0.4441	67.7910
18	24	0.0079	82.9458
20	21	0.0327	77.5743
20	22	0.1929	50.9488
20	23	0.2475	45.0397
22	14	0.2654	72.8043
23	22	0.1563	57.5916
24	25	0.0000	-28.4119
26	18	0.3872	-86.5551
26	27	0.0666	70.6419
27	28	0.0829	56.4499
29	18	4.5985	85.8399
29	30	7.2668	-85.5727
30	F	7.5312	-83.2406
31	29	1.4619	-49.7103
32	29	1.2183	-83.6190
33	31	0.8240	-39.5541
33	34	0.6077	78.2790
34	31	0.5228	-71.0736
34	35	1.0679	87.3547
35	36	0.4240	82.8051
37	36	0.1769	-81.0135
37	35	0.6324	-87.7401
38	2	0.9643	16.2057
39	38	1.0908	46.1330
40	39	1.8822	73.4304
41	42	2.0569	74.4657
42	40	1.8978	73.9657
43	42	0.1577	-20.8837
44	43	0.0847	-78.5880

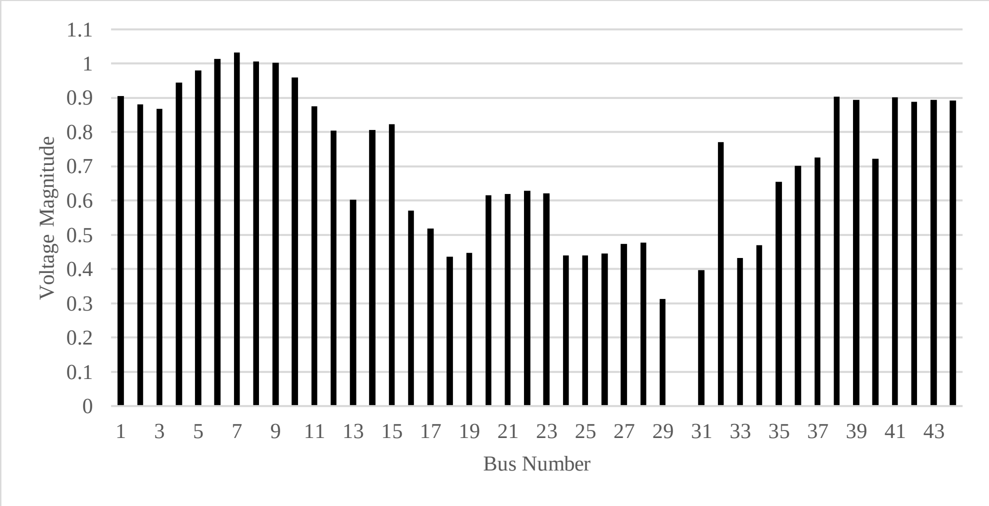

Fig. 5. Curves Of The Bus Voltage Magnitude Per Unit Fault At Tanjungbunga Bus Using The New FFA-ABC Hybrid Method

Next, the comparison of the simulation results of a balanced three-phase short circuit using the New FFA-ABC hybrid method with the FFA method, the ABC method, and the Bus Impedance Matrix method (BIM) for line currents per unit during fault at the Tanjungbunga bus is shown in Table 9.

Table 9 - The Comparison of The Simulation Results of a Balanced Three-Phase Short Circuit For Fault at The Tanjungbunga Bus

From	To	Line Current Magnitude			
		Method			
		FFA-ABC	FFA	ABC	BIM
1	2	0.5434	0.5426	0.5421	0.5444
1	3	0.4888	0.4883	0.4880	0.4893
2	3	0.1119	0.1118	0.1118	0.1119
2	4	1.1232	1.1227	1.1225	1.1237
2	32	1.3369	1.3367	1.3366	1.3371
3	37	0.8456	0.8456	0.8456	0.8457
4	11	1.0688	1.0686	1.0684	1.0691
4	6	0.5195	0.5196	0.5196	0.5195
5	4	0.6950	0.6949	0.6948	0.6951
6	8	0.2819	0.2816	0.2814	0.2822
7	5	0.4615	0.4615	0.4615	0.4616
7	6	0.3678	0.3675	0.3672	0.3682
8	9	0.0921	0.0920	0.0920	0.0922
10	4	0.5129	0.5126	0.5125	0.5131
11	12	1.8329	1.8324	1.8320	1.8336
12	13	2.2775	2.2774	2.2773	2.2776
13	14	0.5839	0.5839	0.5839	0.5839
14	15	0.4224	0.4224	0.4225	0.4224
16	13	0.7917	0.7917	0.7917	0.7917
17	13	2.7352	2.7355	2.7357	2.7349
18	16	0.7948	0.7949	0.7950	0.7947
18	17	2.7726	2.7729	2.7730	2.7723
18	19	0.1463	0.1464	0.1464	0.1461
18	20	0.4441	0.4440	0.4440	0.4441
18	24	0.0079	0.0079	0.0079	0.0079
20	21	0.0327	0.0327	0.0327	0.0328
20	22	0.1929	0.1929	0.1929	0.1928
20	23	0.2475	0.2474	0.2474	0.2475
22	14	0.2654	0.2655	0.2655	0.2653
23	22	0.1563	0.1563	0.1563	0.1563
24	25	0.0000	0.0000	0.0000	0.0000
26	18	0.3872	0.3872	0.3872	0.3873
26	27	0.0666	0.0666	0.0667	0.0666
27	28	0.0829	0.0828	0.0828	0.0829
29	18	4.5985	4.5984	4.5983	4.5986
29	30	7.2668	7.2667	7.2667	7.2668

From	To	Line Current Magnitude			
		Method			
		FFA-ABC	FFA	ABC	BIM
30	F	7.5312	7.5313	7.5313	7.5312
31	29	1.4619	1.4616	1.4614	1.4623
32	29	1.2183	1.2183	1.2183	1.2182
33	31	0.8240	0.8238	0.8237	0.8243
33	34	0.6077	0.6077	0.6076	0.6078
34	31	0.5228	0.5228	0.5228	0.5228
34	35	1.0679	1.0679	1.0679	1.0679
35	36	0.4240	0.4240	0.4239	0.4241
37	36	0.1769	0.1770	0.1770	0.1768
37	35	0.6324	0.6325	0.6325	0.6324
38	2	0.9643	0.9639	0.9637	0.9646
39	38	1.0908	1.0904	1.0902	1.0913
40	39	1.8822	1.8792	1.8773	1.8857
41	42	2.0569	2.0537	2.0517	2.0606
42	40	1.8978	1.8948	1.8929	1.9013
43	42	0.1577	0.1576	0.1576	0.1578
44	43	0.0847	0.0846	0.0845	0.0848

The results of the analysis of the three-phase balanced short circuit of the Sulbagsel electrical system when the fault occurs on the Tanjungbunga bus as shown in Table 9 shows that the system conditions are mostly experiencing voltage instability and voltage drops. Voltage stability conditions occur only on bus 5 (Pinrang bus), bus 6 (Polmas bus), bus 7 (Bakaru bus), bus 8 (Majene bus), bus 9 (Mamuju bus), and bus 10 (Suppa bus) is at 0.95 - 1.05 pu voltage. The magnitude of the largest voltage drop that can cause a voltage collapse is on bus 29 (Sungguminasa bus) of 0.3135 pu. The total of fault current on bus 30 (Tanjungbunga bus), namely, the bus experiencing disturbances, is 7.5312 pu such as shown in Table 8. Comparison of the total fault current on the Tanjungbunga bus (bus 30) using the hybrid FFA-ABC method, FFA method, ABC method, and bus impedance matrix method is shown in Table 9, namely 7.5312 p.u, 7.5313 p.u, 7.5313 p.u, and 7.5312 p.u. This shows that the results obtained by the hybrid FFA-ABC method are the same as the values obtained by the deterministic bus impedance matrix method and the values are smaller compared to the results obtained by the FFA and ABC methods.

The magnitude of the bus voltage and line current from the balanced three-phase short circuit test using the FFA-ABC hybrid method on bus 39 (Palopo bus), a bus that has a large load in the Sulbagsel interconnection electrical system of 49.2 MW is shown in Table 10 and 11. The characteristic curf of the bus voltage magnitude during faults on the Palopo bus per unit using the FFA-ABC hybrid method are shown in Figure 6.

Table 10 - Bus Voltage Magnitude During Fault at Palopo Bus Per Unit Using The Ffa-Abc Hybrid Method

Bus Number	Voltage Magnitude	Angle deegres
1	0.9545	-0.0737
2	0.9224	-2.2914
3	0.9634	-3.6813
4	1.0014	-5.1647
5	1.0214	-5.1047
6	1.0356	-6.0928
7	1.0603	-4.4491
8	1.0154	-9.1708
9	1.0099	-9.6772
10	1.0124	-4.8280
11	1.0126	-7.7893
12	0.9951	-15.4628
13	0.9604	-15.4628
14	0.9518	-22.5190
15	0.9401	-23.0765
16	0.9537	-16.1213
17	0.9607	-15.9178
18	0.9638	-16.0797
19	0.9191	-18.8917
20	0.9754	-27.1028
21	0.9720	-27.4987

Bus Number	Voltage Magnitude	Angle deegres
22	0.9625	-27.7110
23	0.9660	-27.6998
24	0.9736	-16.0797
25	0.9736	-16.0798
26	0.9739	-16.7792
27	0.9330	-23.3369
28	0.9164	-24.3799
29	0.9792	-13.3609
30	0.9688	-14.5931
31	0.9964	-6.0186
32	0.9267	-4.9553
33	1.0147	-2.7923
34	1.0052	-5.0192
35	0.9906	-8.1136
36	1.0046	-8.7991
37	0.9797	-7.9226
38	0.2573	17.0360
39	0.0000	0.0000
40	0.0220	129.9059
41	0.0881	177.9377
42	0.0867	176.4628
43	0.0975	174.5932
44	0.1118	173.2640

Table 11 - Line Currents For Fault at Palopo Bus Per Unit Using The Ffa-Abc Hybrid Method

From Bus	To Bus	Current Magnitude	Angle deegres
1	2	0.6640	-34.2489
1	3	0.4788	15.7881
2	3	0.2243	72.3267
2	4	1.2388	70.3474
2	32	0.5086	10.3029
2	38	1.7901	-89.6427
3	37	0.4388	22.4125
4	11	0.5965	14.2673
4	6	0.2820	70.5420
5	4	0.3880	-76.4136
6	8	0.3028	-12.1252
7	5	0.3617	-60.7453
7	6	0.4045	-28.6998
8	9	0.1015	-23.6162
10	4	0.4266	-51.1277
11	12	1.1375	-14.3991
12	13	1.0666	-18.5985
13	14	0.2988	-23.1650
13	16	0.3215	-31.4498
13	17	0.2465	1.3203
14	15	0.2175	-46.0274
14	22	0.1155	10.3527
16	18	0.0556	88.0979
17	18	0.1348	47.6650
18	16	0.0593	-81.5219
18	26	0.5747	39.3612
18	19	0.7096	-32.9783
18	20	0.4487	-18.0658
18	24	0.0176	73.9213
20	21	0.0597	-25.4290
20	22	0.1354	-50.0912
20	23	0.2739	-41.6098
23	22	0.0489	-85.8283
24	25	0.0000	28.3152
26	27	0.2800	-40.5619
27	28	0.2799	-39.9630
29	18	1.8254	-24.7992
29	30	0.5428	-30.7995
31	29	1.9028	-9.1024

From Bus	To Bus	Current Magnitude	Angle deegres
32	29	0.4113	18.7409
33	31	1.2088	-1.5007
33	34	0.6040	-9.1240
34	31	0.1571	-17.5218
34	35	0.3115	-6.1922
35	36	0.1623	53.9284
37	36	0.2046	51.9952
37	35	0.0983	75.7059
38	2	1.7906	89.9077
38	39	1.7611	-57.3911
39	F	1.9959	-29.4901
40	39	0.1279	39.9059
40	42	0.1913	-73.2913
42	41	0.2010	-33.3731
43	42	0.1686	86.7145
44	43	0.1079	81.5463

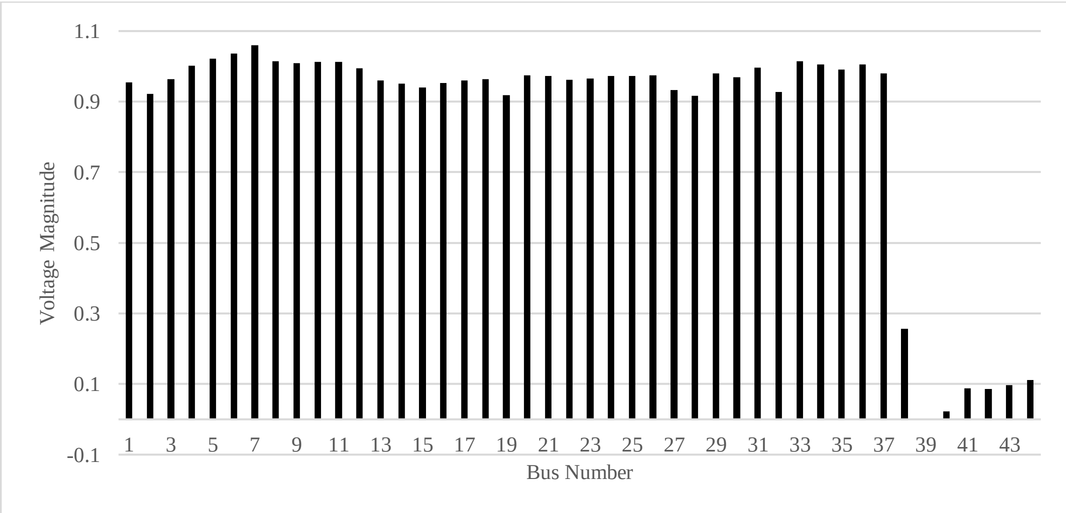

Fig. 6. Curves of The Bus Voltage Magnitude Per Unit Fault at Palopo Bus Using The New FFA-ABC Hybrid Method

Next, the comparison of the simulation results of a balanced three-phase short circuit using the FFA-ABC hybrid method with the FFA method, the ABC method, and the Bus Impedance Matrix method (BIM) for line currents per unit during fault at the Palopo bus is shown in Table 12.

Table 12 - The Comparison of The Simulation Results of A Balanced Three-Phase Short Circuit For Fault at The Palopo Bus

From	To	Line Current Magnitude			
		Method			
		FFA-ABC	FFA	ABC	BIM
1	2	0.6640	0.6631	0.6626	0.6649
1	3	0.4788	0.4782	0.4779	0.4794
2	3	0.2243	0.2243	0.2243	0.2244
2	4	1.2388	1.2385	1.2382	1.2393
2	32	0.5086	0.5081	0.5078	0.5092
2	38	1.7901	1.7901	1.7901	1.7902
3	37	0.4388	0.4383	0.4380	0.4393
4	11	0.5965	0.5959	0.5955	0.5972
4	6	0.2820	0.2820	0.2820	0.2820
5	4	0.3880	0.3879	0.3879	0.3882
6	8	0.3028	0.3025	0.3023	0.3032
7	5	0.3617	0.3617	0.3616	0.3618
7	6	0.4045	0.4041	0.4039	0.4049
8	9	0.1015	0.1014	0.1014	0.1016
10	4	0.4266	0.4263	0.4262	0.4269
11	12	1.1375	1.1364	1.1357	1.1388
12	13	1.0666	1.0656	1.0649	1.0677

From	To	Line Current Magnitude			
		Method			
		FFA-ABC	FFA	ABC	BIM
13	14	0.2988	0.2985	0.2983	0.2991
13	16	0.3215	0.3212	0.3210	0.3218
13	17	0.2465	0.2461	0.2459	0.2469
14	15	0.2175	0.2173	0.2171	0.2177
14	22	0.1155	0.1154	0.1153	0.1156
16	18	0.0556	0.0555	0.0554	0.0558
17	18	0.1348	0.1344	0.1341	0.1353
18	16	0.0593	0.0592	0.0591	0.0595
18	26	0.5747	0.5745	0.5743	0.5750
18	19	0.7096	0.7090	0.7085	0.7104
18	20	0.4487	0.4483	0.4480	0.4492
18	24	0.0176	0.0176	0.0176	0.0176
20	21	0.0597	0.0596	0.0596	0.0597
20	22	0.1354	0.1352	0.1351	0.1355
20	23	0.2739	0.2736	0.2735	0.2742
23	22	0.0489	0.0488	0.0488	0.0490
24	25	0.0000	0.0000	0.0000	0.0000
26	27	0.2800	0.2797	0.2795	0.2803
27	28	0.2799	0.2797	0.2795	0.2803
29	18	1.8254	1.8238	1.8228	1.8272
29	30	0.5428	0.5423	0.5420	0.5434
31	29	1.9028	1.9011	1.9000	1.9048
32	29	0.4113	0.4109	0.4106	0.4117
33	31	1.2088	1.2077	1.2070	1.2100
33	34	0.6040	0.6035	0.6032	0.6046
34	31	0.1571	0.1570	0.1569	0.1573
34	35	0.3115	0.3113	0.3111	0.3117
35	36	0.1623	0.1621	0.1621	0.1624
37	36	0.2046	0.2045	0.2044	0.2048
37	35	0.0983	0.0982	0.0982	0.0984
38	2	1.7906	1.7906	1.7906	1.7906
38	39	1.7611	1.7611	1.7611	1.7611
39	F	1.9959	1.9959	1.9959	1.9959
40	39	0.1279	0.1280	0.1281	0.1278
40	42	0.1913	0.1912	0.1911	0.1914
42	41	0.2010	0.2007	0.2005	0.2014
43	42	0.1686	0.1686	0.1686	0.1687
44	43	0.1079	0.1079	0.1079	0.1079

The results of the analysis of the three-phase balanced short circuit of the Sulbagsel electrical system when the fault occurs on the Palopo bus as shown in Table 10 show that the condition of voltage instability occurs on the bus 2 (Sidrap bus) of 0.9224 pu, bus 7 (Bakaru bus) of 1.0603 pu, bus 15 (Pangkep 70 bus) of 0.9401 pu, bus 19 (Panakukang bus) of 0.9191 pu, bus 27 (Tallo Lama 70 bus) of 0.9330 pu, bus 28 (Bontoala bus) of 0.9164 pu, and bus 32 (Maros bus) of 0.9267 pu. The magnitude of the voltage drop that can cause a voltage collapse is on the bus 38 (Makale bus) of 0.2573 pu, bus 40 (LTUPA 275 bus) of 0.0220 pu, bus 41 (PLTA Poso bus) of 0.0881 pu, bus 42 (Pamona 275 bus) of 0.0867 pu, bus 43 (Pamona 150 bus) of 0.0975, and bus 44 (Poso bus) of 0.1118 pu. While, the magnitude of the largest voltage drop that can cause a voltage collapse is on the bus 40 (LTUPA 275 bus) of 0.0220 pu. The total amount of fault current on bus 39 (Palopo bus), namely, the bus experiencing disturbances, is 1.9959 pu such as shown in Table 11. Comparison of the total fault current on the Palopo bus (bus 39) using the hybrid FFA-ABC method, FFA method, ABC method, and bus impedance matrix method is shown in Table 12, namely 1.9959 p.u, 1.9959 p.u, 1.9959 p.u, and 1.9959 p.u. This shows that the results obtained by the hybrid FFA-ABC method are the same as the values obtained by the FFA method, ABC method, and deterministic bus impedance matrix method at the fault point (Palopo bus). However, the magnitude of the line current compared to other line currents shows that the results obtained by the Hybrid FFA-ABC method are closer to the values obtained by the deterministic bus impedance matrix method compared to the FFA method or ABC method.

The magnitude of the bus voltage and line current from the balanced three-phase short circuit test using the FFA-ABC hybrid method on bus 2 (Sidrap bus), a bus closest bus from Sengkang bus (Slack bus) that has a load in the Sulbagsel interconnection electrical system of 26.5 MW is shown in Table 13 and 14. The characteristic curf of the bus voltage magnitude during faults on the sidrap bus per unit using the FFA-ABC hybrid method are shown in Figure 7.

Table 13. Bus Voltage Magnitude During Fault at Sidrap Bus Per Unit Using The Ffa-Abc Hybrid Method

Bus Number	Voltage Magnitude	Angle deegres
1	0.3204	-2.7060
2	0.0000	0.0000
3	0.4218	-5.2068
4	0.6134	-8.1263
5	0.7451	-8.0766
6	0.8818	-8.3715
7	0.8707	-7.0349
8	0.9548	-10.4908
9	0.9644	-10.8286
10	0.6490	-8.0862
11	0.7473	-8.4761
12	0.7715	-10.3351
13	0.7508	-12.7802
14	0.8721	-21.2536
15	0.8756	-22.4641
16	0.7403	-12.8127
17	0.7314	-11.8369
18	0.7135	-10.5890
19	0.6966	-12.8351
20	0.8044	-19.6556
21	0.8045	-19.9684
22	0.8038	-20.6940
23	0.8023	-20.4016
24	0.7207	-10.5889
25	0.7207	-10.5889
26	0.7239	-11.1320
27	0.7166	-15.9283
28	0.7099	-16.8516
29	0.6841	-7.3348
30	0.6826	-8.1280
31	0.6743	0.3218
32	0.1320	5.7628
33	0.6769	3.7334
34	0.6570	1.5049
35	0.5758	-1.6145
36	0.5687	-2.1316
37	0.5300	-2.7138
38	0.2613	79.8578
39	0.3386	87.7138
40	0.2921	107.4715
41	0.4154	160.4674
42	0.4092	158.9926
43	0.4206	158.1160
44	0.4318	157.0742

Table 14 - Line Currents For Fault At Sidrap Bus Per Unit Using The New Ffa-Abc Hybrid Method

From Bus	To Bus	Current Magnitude	Angle deegres
1	2	4.3674	-84.3993
1	3	0.7998	86.3164
2	F	18.9697	-80.0014
3	2	2.0049	-79.5977
4	2	8.2103	-82.5701
4	11	1.6722	87.0117
5	4	2.5496	-82.2421
6	4	1.9695	-82.9256
6	8	0.4105	70.6928
7	5	1.1082	-74.8704
7	6	0.2425	35.4579

From Bus	To Bus	Current Magnitude	Angle deegres
8	9	0.1008	59.2833
10	4	1.2132	-81.8158
11	12	0.8345	51.4495
12	13	0.4368	-28.1448
13	14	0.4313	28.2463
13	16	0.2593	-84.1713
14	15	0.2746	17.5846
14	22	0.0907	-88.9784
17	13	0.7305	60.9185
18	16	0.2217	46.5184
18	17	0.7602	52.8971
18	26	0.4619	61.5419
18	19	0.3574	-14.5535
18	20	0.3616	21.9575
18	24	0.0130	79.4290
20	21	0.0349	9.1285
20	22	0.1199	6.0675
20	23	0.2121	-2.8754
23	22	0.0613	28.4074
24	25	0.0000	25.2309
26	27	0.1460	-20.4486
27	28	0.1571	-17.9034
29	18	1.8539	35.8110
29	30	0.2230	-7.4500
31	29	1.3597	10.9519
32	29	1.4788	87.7950
32	2	1.5437	-75.9162
33	31	0.8186	19.1802
33	34	0.4877	-26.3438
34	31	0.1613	61.3889
34	35	0.4862	-51.8449
35	36	0.0794	-37.9772
35	37	0.4059	-62.9213
36	37	0.2680	-78.3401
37	3	0.6513	-67.2734
38	2	0.6834	-0.4467
39	38	0.5982	37.4804
39	40	0.6816	-59.4975
40	42	0.8408	-58.1908
42	41	0.9481	-50.8434
43	42	0.1965	56.2237
44	43	0.1005	41.4168

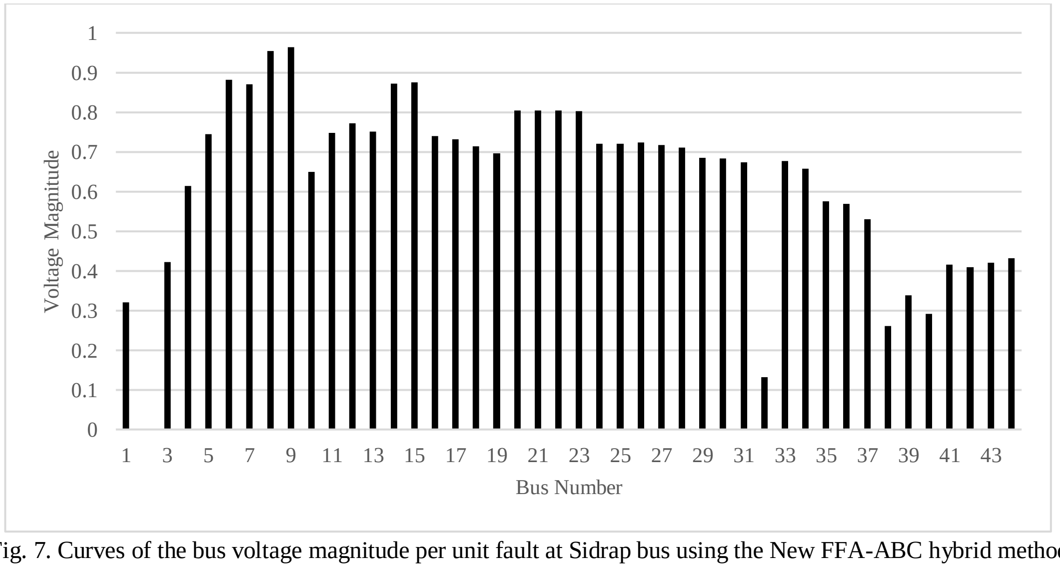

Fig. 7. Curves of the bus voltage magnitude per unit fault at Sidrap bus using the New FFA-ABC hybrid method

Next, the comparison of the simulation results of a balanced three-phase short circuit using the FFA-ABC hybrid method with the FFA method, the ABC method, and the Bus Impedance

Matrix method (BIM) for line currents per unit during fault at the sidrap bus is shown in Table 15.

Table 15 - The Comparison of The Simulation Results of a Balanced Three-Phase Short Circuit For Fault at The Sidrap Bus

From	To	Line Current Magnitude			
		Method			
		FFA-ABC	FFA	ABC	BIM
1	2	4.3674	4.3674	4.3674	4.3674
1	3	0.7998	0.7998	0.7998	0.7998
2	F	18.9697	18.9700	18.9701	18.9695
3	2	2.0049	2.0049	2.0049	2.0048
4	2	8.2103	8.2103	8.2104	8.2102
4	11	1.6722	1.6721	1.6721	1.6723
5	4	2.5496	2.5495	2.5495	2.5497
6	4	1.9695	1.9695	1.9696	1.9694
6	8	0.4105	0.4106	0.4106	0.4105
7	5	1.1082	1.1082	1.1082	1.1082
7	6	0.2425	0.2423	0.2422	0.2427
8	9	0.1008	0.1008	0.1008	0.1008
10	4	1.2132	1.2130	1.2130	1.2133
11	12	0.8345	0.8341	0.8338	0.8350
12	13	0.4368	0.4361	0.4356	0.4376
13	14	0.4313	0.4312	0.4311	0.4314
13	16	0.2593	0.2593	0.2593	0.2594
14	15	0.2746	0.2745	0.2745	0.2747
14	22	0.0907	0.0908	0.0908	0.0906
17	13	0.7305	0.7309	0.7311	0.7300
18	16	0.2217	0.2218	0.2219	0.2216
18	17	0.7602	0.7605	0.7607	0.7598
18	26	0.4619	0.4618	0.4617	0.4620
18	19	0.3574	0.3569	0.3566	0.3580
18	20	0.3616	0.3613	0.3612	0.3619
18	24	0.0130	0.0130	0.0130	0.0130
20	21	0.0349	0.0348	0.0348	0.0349
20	22	0.1199	0.1199	0.1198	0.1200
20	23	0.2121	0.2119	0.2118	0.2123
23	22	0.0613	0.0613	0.0613	0.0613
24	25	0.0000	0.0000	0.0000	0.0000
26	27	0.1460	0.1458	0.1457	0.1462
27	28	0.1571	0.1569	0.1568	0.1573
29	18	1.8539	1.8530	1.8524	1.8550
29	30	0.2230	0.2227	0.2225	0.2234
31	29	1.3597	1.3585	1.3578	1.3611
32	29	1.4788	1.4788	1.4787	1.4788
32	2	1.5437	1.5437	1.5437	1.5436
33	31	0.8186	0.8178	0.8173	0.81
33	34	0.4877	0.4874	0.4872	0.4880
34	31	0.1613	0.1612	0.1611	0.1614
34	35	0.4862	0.4861	0.4860	0.4862
35	36	0.0794	0.0795	0.0795	0.0794
35	37	0.4059	0.4059	0.4059	0.4059
36	37	0.2680	0.2680	0.2679	0.2681
37	3	0.6513	0.6513	0.6514	0.6512
38	2	0.6834	0.6834	0.6834	0.6834
39	38	0.5982	0.5982	0.5981	0.5983
39	40	0.6816	0.6806	0.6799	0.6829
40	42	0.8408	0.8394	0.8385	0.8423
42	41	0.9481	0.9467	0.9457	0.9499
43	42	0.1965	0.1965	0.1965	0.1965
44	43	0.1005	0.1005	0.1004	0.1005

The results of the analysis of the three-phase balanced short circuit of the Sulbagsel electrical system when the fault occurs on the Sidrap bus as shown in Table 13 show that the condition of voltage stability only occurs on bus 8 (Majene bus) of 0.9548 pu, and bus 9 (Mamuju bus) of 0.9644 pu. While, the magnitude of the largest voltage drop that can cause a voltage collapse is on the bus 38 (Makale bus) of 0.2613 pu. Comparison of the total fault current on the Sidrap bus using the hybrid FFA-ABC method, FFA method, ABC method, and bus impedance matrix method is shown in Table 15, namely 18.9697 p.u, 18.9700 p.u, 18.9701 and 18.9695 p.u. This shows that the results obtained with the hybrid FFA-ABC method are close to the results obtained by the bus impedance matrix method with smaller errors when compared with the FFA method and the ABC method. Likewise, the magnitude of the line current flowing in other lines shows that the value obtained by the FFA-ABC hybrid method is smaller than the FFA method or ABC method and is close to the value obtained by the deterministic bus impedance matrix method.

The magnitude of the bus voltage and line current from the balanced three-phase short circuit test using the FFA-ABC hybrid method on bus 44 (Poso bus), a bus that further buses from Sengkang bus (Slack bus) that has a load in the Sulbagsel interconnection electrical system of 26.5 MW is shown in Table 16 and 17. The characteristic curf of the bus voltage magnitude during faults on the Palopo bus per unit using the FFA-ABC hybrid method are shown in Figure 8.

Table 16 - Bus Voltage Magnitude During Fault at Poso Bus Per Unit Using The Ffa-Abc Hybrid Method

Bus Number	Voltage Magnitude	Angle deegres
1	0.9932	0.3234
2	0.9788	-1.7822
3	0.9964	-3.3481
4	1.0249	-4.8515
5	1.0380	-4.8300
6	1.0447	-5.8954
7	1.0716	-4.2247
8	1.0189	-9.0629
9	1.0125	-9.5857
10	1.0343	-4.5127
11	1.0288	-7.6194
12	1.0088	-10.1596
13	0.9736	-15.4724
14	0.9569	-22.5443
15	0.9442	-23.0743
16	0.9672	-16.1560
17	0.9753	-15.9766
18	0.9800	-16.1838
19	0.9336	-19.0363
20	0.9872	-27.3754
21	0.9836	-27.7782
22	0.9735	-27.9729
23	0.9774	-27.9709
24	0.9899	-16.1838
25	0.9899	-16.1839
26	0.9900	-16.8929
27	0.9475	-23.5516
28	0.9302	-24.6066
29	0.9981	-13.4511
30	0.9873	-14.7067
31	1.0170	-6.1017
32	0.9757	-4.6021
33	1.0363	-2.8738
34	1.0275	-5.0883
35	1.0168	-8.1156
36	1.0321	-8.7929
37	1.0078	-7.8475
38	0.7111	24.8029
39	0.5996	37.9757
40	0.3739	55.7546
41	0.1598	109.1729
42	0.1574	107.6981
43	0.1071	111.3649
44	0.0000	0.0000

Table 17 - Line Currents For Fault at Poso Bus Per Unit Using The Ffa-Abc Hybrid Method

From Bus	To Bus	Current Magnitude	Angle deegres
1	2	0.5348	-14.0348
1	3	0.5008	10.7383
2	3	0.1564	44.8684
2	4	0.9471	52.7927
2	32	0.5673	1.3398
3	37	0.4730	18.1009
4	11	0.6252	5.3742
4	6	0.2099	52.1764
5	4	0.2543	-77.4128
6	8	0.3228	-16.1260
7	5	0.3158	-58.9657
7	6	0.4249	-30.1185
8	9	0.1080	-26.4137
10	4	0.3844	-46.3485
11	12	1.1940	-16.2725
12	13	1.1048	-18.0579
13	14	0.3044	-26.9930
13	16	0.3299	-28.9891
13	17	0.2814	10.3879
14	15	0.2261	-49.6119
14	22	0.1228	13.4802
16	18	0.0709	82.9271
17	18	0.1889	51.5834
18	16	0.0735	-88.4193
18	26	0.5854	38.4537
18	19	0.7334	-33.2447
18	20	0.4616	-19.6291
18	24	0.0179	73.8169
20	21	0.0618	-26.2790
20	22	0.1406	-52.3095
20	23	0.2819	-43.0505
23	22	0.0540	-88.7125
24	25	0.0000	28.6489
26	27	0.2892	-40.9029
27	28	0.2887	-40.4272
29	18	1.8987	-27.5190
29	30	0.5643	-31.0244
31	29	1.9456	-9.7679
32	29	0.4258	7.1541
33	31	1.2386	-2.1248
33	34	0.6112	-8.1746
34	31	0.1665	-20.4412
34	35	0.3072	-2.2754
35	36	0.1717	56.0668
37	36	0.2083	48.7923
37	35	0.0898	64.2864
38	2	1.2298	54.5905
39	38	1.2792	83.2699
39	40	1.5609	-77.1342
40	42	0.7910	-50.6758
41	42	0.3646	77.8621
42	43	0.7667	26.7206
43	44	0.7968	28.2656
44	F	0.8457	34.3133

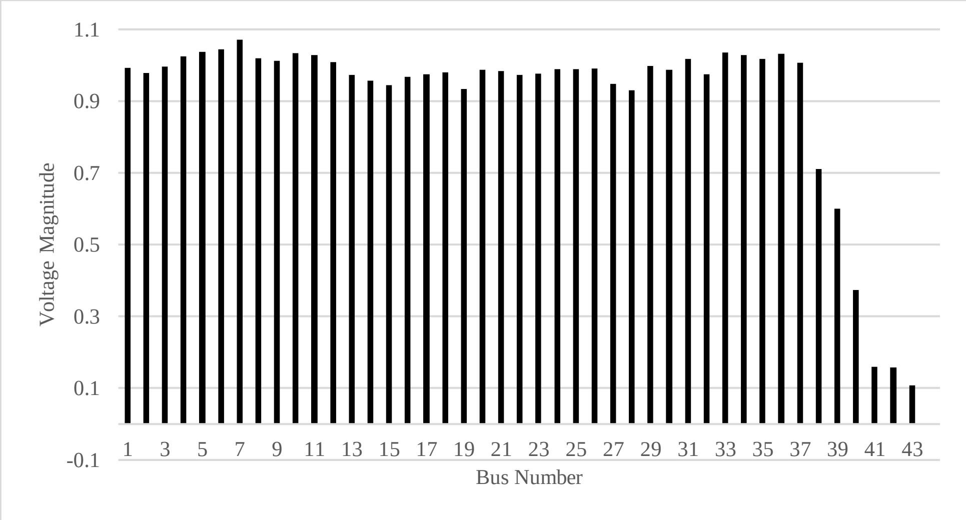

Fig. 8. Curves Of The Bus Voltage Magnitude Per Nit Fault At Poso Bus Using The New FFA-ABC Hybrid Method

Next, the comparison of the simulation results of a balanced three-phase short circuit using the new FFA-ABC hybrid method with the FFA method, the ABC method, and the Bus Impedance Matrix method (BIM) for line currents per unit during fault at the poso bus is shown in Table 18.

Table 18. The Comparison of The Simulation Results of A Balanced Three-Phase Short Circuit For Fault at The Poso Bus

From	To	Line Current Magnitude			
		Method			
		FFA-ABC	FFA	ABC	BIM
1	2	0.5348	0.5338	0.5332	0.5360
1	3	0.5008	0.5002	0.4999	0.5015
2	3	0.1564	0.1564	0.1564	0.1564
2	4	0.9471	0.9466	0.9463	0.9477
2	32	0.5673	0.5668	0.5664	0.5680
3	37	0.4730	0.4726	0.4723	0.4736
4	11	0.6252	0.6246	0.6242	0.6260
4	6	0.2099	0.2099	0.2099	0.2100
5	4	0.2543	0.2542	0.2541	0.2545
6	8	0.3228	0.3225	0.3223	0.3232
7	5	0.3158	0.3157	0.3157	0.3158
7	6	0.4249	0.4246	0.4244	0.4253
8	9	0.1080	0.1079	0.1079	0.1081
10	4	0.3844	0.3841	0.3839	0.3847
11	12	1.1940	1.1929	1.1922	1.1953
12	13	1.1048	1.1038	1.1031	1.1060
13	14	0.3044	0.3042	0.3040	0.3048
13	16	0.3299	0.3296	0.3294	0.3302
13	17	0.2814	0.2810	0.2807	0.2819
14	15	0.2261	0.2259	0.2257	0.2263
14	22	0.1228	0.1226	0.1226	0.1229
16	18	0.0709	0.0707	0.0706	0.0710
17	18	0.1889	0.1884	0.1881	0.1894
18	16	0.0735	0.0733	0.0732	0.0736
18	26	0.5854	0.5852	0.5850	0.5857
18	19	0.7334	0.7327	0.7322	0.7342
18	20	0.4616	0.4611	0.4609	0.4621
18	24	0.0179	0.0179	0.0179	0.0179
20	21	0.0618	0.0617	0.0617	0.0618
22	22	0.1406	0.1405	0.1404	0.1408
20	23	0.2819	0.2816	0.2814	0.2822
23	22	0.0540	0.0539	0.0539	0.0541
24	25	0.0000	0.0000	0.0000	0.0000
26	27	0.2892	0.2889	0.2887	0.2895
27	28	0.2887	0.2884	0.2883	0.2890
29	18	1.8987	1.8971	1.8961	1.9005

From	To	Line Current Magnitude			
		Method			
		FFA-ABC	FFA	ABC	BIM
29	30	0.5643	0.5638	0.5635	0.5649
31	29	1.9456	1.9438	1.9427	1.9476
32	29	0.4258	0.4254	0.4251	0.4262
33	31	1.2386	1.2375	1.2368	1.2399
33	34	0.6112	0.6107	0.6104	0.6118
34	31	0.1665	0.1664	0.1663	0.1667
34	35	0.3072	0.3070	0.3068	0.3074
35	36	0.1717	0.1716	0.1715	0.1719
37	36	0.2083	0.2081	0.2080	0.2084
37	35	0.0898	0.0897	0.0896	0.0899
38	2	1.2298	1.2296	1.2294	1.2301
39	38	1.2792	1.2790	1.2788	1.2795
39	40	1.5609	1.5590	1.5578	1.5631
40	42	0.7910	0.7909	0.7908	0.7911
41	42	0.3646	0.3641	0.3637	0.3653
42	43	0.7667	0.7667	0.7667	0.7666
43	44	0.7968	0.7968	0.7968	0.7967
44	F	0.8457	0.8457	0.8458	0.8457

The results of the analysis of the three-phase balanced short circuit of the Sulbagsel electrical system when the fault occurs on the Poso bus (bus 44) as shown in Table 16 show that the condition of voltage instability occurs on bus 7 (Bakaru 150 kV bus) of 1.0716 pu, bus 15 (Tonasa 70 kV bus) of 0.9442 p.u, bus 19 (Panakukang 150 kV bus) of 0.9336 p.u, bus 27 (Tallo Lama 70 kV) of 0.9475 p.u, and bus 28 (Bontoala 150 kV bus) of 0.9302 pu. While, the magnitude of the largest voltage drop that can cause a voltage collapse is on the bus 40 (Ltupa 150 kV bus) of 0.3739 pu, bus 41 (PLTA Poso 150 kV bus) of 0.1598 p.u, bus 42 (Pamona 275 kV bus) of 0.1574 p.u, and bus 43 (Pamona 150 kV bus) of 0.1071 p.u. Comparison of the total fault current on the Poso bus using the hybrid FFA-ABC method, FFA method, ABC method, and bus impedance matrix method is shown in Table 18, namely 0.8457 p.u, 0.8457 p.u, 0.8458 and 0.8457 p.u. This shows that the results obtained by the hybrid FFA-ABC method are the same as the FFA method and the deterministic bus impedance matrix method but are better than the ABC method. However, the channel current flowing in other channels shows that the value obtained by the hybrid FFA-ABC method is closer to the value obtained by the deterministic bus impedance matrix method.

5. Conclusion

This paper proposes the new FFA-ABC hybrid method, which is able to solve the problem of balanced three-phase short circuits in the Sulbagsel electrical system with the smallest error compared to the FFA method and ABC method. The simulation results of the five tested cases using the new FFA-ABC hybrid method show that the largest fault current occurs when the fault is close to the slack bus generator, and the smallest fault current occurs when the fault is farthest from the slack bus generator. Future research will consider analyzing the unbalanced three-phase short circuit in the Sulbagsel electrical system by using the new FFA-ABC hybrid method.

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